Applied Energy 221 (2018) 148–160

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

On the relation between urban climate and energy performance of buildings. A three-years experience in Rome, Italy

Michele Zinzi[a,*], Emiliano Carnielo[b], Benedetta Mattoni[a,c]

[a] ENEA, Via Anguillarese 301, 00123 Rome, Italy
[b] University of Rome Tre, Engineering Department, Via della Vasca Navale, 00100 Rome, Italy
[c] University of Rome "Sapienza", Department of Astronautic, Electric and Energy Engineering, Via Eudossiana 18, 00100 Rome, Italy

HIGHLIGHTS

- Summer urban heat island up to 2.8 °C and winter urban heat island up to 1 °C.
- Reduction of urban heating degree days up to 18%.
- Increase of urban cooling degree days up to 157%.
- Building cooling energy increase by 22–26% per urban heat island degree.
- Building heating energy reduction by 18–24% per urban heat island degree.

ARTICLE INFO

Keywords:
Urban heat island
Urban thermal monitoring
Energy performance of buildings

ABSTRACT

Climatic conditions strongly affect the energy performance of buildings, and due to the synergy between global climate change and the Urban Heat Island (UHI) effect, the climatic conditions inside and outside the city are highly different. However, weather data collected at airports are commonly used for building energy simulations and these data do not take into account real temperature distribution in cities. Many studies in the literature address the topic but mostly considering only a couple of urban and non-urban stations. In this paper, the urban climate in Rome, Italy, is analysed after monitoring of the air temperature and relative humidity in four selected neighbourhoods and one reference station from October 2014 until September 2017. Rome is characterised by a composite urban pattern and high variability of building types, of which the four selected areas are representative. The heating degree days decrease up to 18% and cooling degree days increase up to 157% in the urban area with respect to the rural reference and the area most affected by the UHI is the city centre. The UHI is more intense in summer than in winter (average increase between 0.7 °C and 1 °C); while the diurnal and nocturnal UHI depends on the season and the neighbourhood. Then, the energy performance of a representative apartment block and a typical office building was computed using the measured data. Regarding the predicted energy performance, comparing the four urban sites and the reference site, the UHI causes a reduction of heating consumption up to 21% in residential building and 18% in the office building. An increase of cooling consumption up to 74% is instead computed for the residential building and up to 53% for the office building.

1. Introduction

Buildings are responsible for the highest energy consumption and CO_2 emissions in Europe, with a share of respectively 40% and 36% [1]. Energy policies were developed in the past years to achieve relevant energy savings in the building sector. In the EU, for instance, the Energy Performance of Building Directive [2] outlines a general framework for assessing the energy performance of new buildings and existing buildings to be renovated. In Italy, as in most European countries, the first measure which has been set is the improvement of the energy performance for space heating since it is considered the most energy consuming service [3]. Global climate change, however, is outlining new scenarios, based on a strong increase of cooling demand in buildings. The trend is exacerbated by urban sprawl, which leads to the generation of the Urban Heat Island (UHI) effect, namely the strongest local climate change, defined as the increase of urban temperature compared to that of the countryside surrounding the city, due to urban sprawl, in increasing synergy with global warming [4–7]. The magnitude of UHIs

* Corresponding author.
E-mail address: michele.zinzi@enea.it (M. Zinzi).

https://doi.org/10.1016/j.apenergy.2018.03.192
Received 27 December 2017; Received in revised form 14 March 2018; Accepted 31 March 2018
Available online 17 April 2018
0306-2619/ © 2018 Elsevier Ltd. All rights reserved.

Nomenclature

UHI	Urban Heat Island
UCI	urban cooling island
TMY	Typical Meteorological Year
GIS	geographic information system
CCZ	city centre zone
SP1	semi-peripheral zone 1
SP2	semi-peripheral zone 2
PE	peripheral zone
RE	reference station
HDD	heating degree days
CDD	cooling degree days

depends on several aspects: urban texture and morphology, radiative and thermal properties of the construction materials which create favourable conditions for absorption and storage of solar irradiation, local wind speed and direction, anthropogenic heat, the presence of green areas and water. The choice of the extra-urban microclimatic reference also play an important role in the assessment of UHI [8–10]. UHI is crucial for several applied energy issues: to predict the energy performance of single buildings and whole districts; to provide realistic microclimatic data for reliable energy system assessments at different scales; to adequately implement urban overheating mitigation strategies.

Climate change is reshaping the energy performance of building and cities. The variation of the energy performance of buildings for space heating and cooling in the future (till the year 2030) was investigated by Cartalis et al. [11]. With a simulation model which assesses climatic changes on the basis of climatic scenarios they found that heating and cooling degree days will decrease and increase, respectively, compared to the respective amounts for the year 1990. The limitation of these climatic models, as highlighted by the authors, is due to the lack of data in existing and future emission inventories of greenhouse gases and the impossibility of predicting potential changes in the future.

In another study, Lam et al. [12] assessed the impact of climate change on the electricity consumption for air conditioning of a commercial building stock in subtropical Hong Kong by using 1979–2008 meteorological data. They developed a regression based on measured data and they estimated the energy consumption from 2009 to 2100, computing a mean increase of 12.5% of electricity consumption for the 92-year period. Ahmed et al. [13] computed that in the State of New South Wales, Australia, the electricity demand will increase by 2050 between 2.7% and 4.5% during summer and spring season because of global climate change.

Greater impacts are computed when the thermal response of the city is investigated. A comprehensive review by Santamouris [14] screened many relevant studies finding that the impact of UHI on cooling loads is statistically significant and account for about 13% on the average. The influence of urban temperatures on the energy use for air conditioning in arid regions was explored by Radhi and Sharples [15] in Bahrain. They used numerical modelling to assess wind flow, temperatures and heat distribution fluxes, showing an increase by up to 10% of the electricity consumption for cooling in urban regions from April to October. Zhou et al. also achieved similar results for the city of Beijing in 2005, where it was assessed that air conditioning, due to the influence of the local climate (UHI, relative humidity and cumulative effect), is responsible for approximately the 12% of total summer electricity consumption, reaching the 20% during peak periods [16]. The UHI in Beijing was studied considering the average temperature of the entire urban area and the average temperature of several locations in the surrounding rural areas. The impact of UHI in London was studied by Kolokotroni et al. [17,18], who computed the energy performance of an office building using hourly temperature data recorded by 20 microclimatic stations within the urban canopy layer during one year of monitoring (1999–2000). They found that cooling increased between 27% and 45% and heating loads are reduced by more than 60% in the city centre. In Modena, Italy, Magli et al. [19] considered a rural and an urban reference station recording hourly temperature data for one year. The heating energy loads of a commercial building associated with the rural station was 20% higher than the urban one, while the cooling loads decreased by about 10%. Street et al. [20] developed a similar analysis for the city of Boston, U.S.A., using temperature data from one urban station and two rural stations; heating loads decreased by 14% in the urban station for a detached house, while the cooling demand increased by about 3–9%. An analysis of residential buildings was carried out by Chen et al. [21] for the city of Melbourne, Australia, comparing urban and rural temperature measured by two stations from a one-year campaign. They found that the UHI causes an increase of cooling uses by 10% and 17% for respectively existing and new buildings, and the analogous space heating decrease is respectively 5% and 7%. Paolini et al. [22] for a residential building, representative of the building stock of Milan, Italy, computed the heating, cooling and dehumidification loads with urban and rural data for seven years (2002–2008), including the European heat wave of 2003. They found that the UHI reduces heating loads by 12–16% and dehumidification loads by 74–78%, while it increases cooling loads by 39–41%. They found the largest gap in cooling needs to occur right during heatwaves, with a greater indoor urban-rural air temperature difference during the heatwave than during the seven-year average. This finding is consistent with the synergy between heat islands and heatwaves [23]. Giannopoulou et al. [24] have recorded temperature from 25 fixed stations in Athens in the year 2009 to analyse the characteristics of the heat island phenomenon during the summer season. The stations were grouped into five zones, showing statistically different mean and maximum daily air temperatures among the five areas. Data from the literature about the impact of the urban heat island on the peak electricity consumption were reviewed by Santamouris et al. [25]: average results show an increase between 0.45% and 4.6% per each degree of ambient temperature rise.

According to these studies, it emerges the importance of the quality of meteorological data to accurately predict the energy and thermal response of buildings in the real urban or rural context [26]. This is particularly critical for cities, whose climatic data are often collected at airports, outside of the urban belt, and thus are not representative of the urban local climate conditions. The impact of seven different climatic input files for two years on energy consumption of a residential building in Athens was evaluated by Hassid et al. [27]. Their results show high differences in cooling energy consumption and peak power due to the different input files in particular when comparing Athens meteorological year with measured data in urban areas.

Starting from the evident impact of the UHI on building energy consumption, relevant studies were addressed to estimate the potentials of mitigation strategies [28]. A large simulation study on mitigation strategies for five pilot cities in the USA was carried out by Akbari and Konopacki [29], where direct impacts (building related technologies) and indirect effects (energy savings arising from reduced urban temperatures) were computed. They calculated the annual cooling savings and heating penalties, showing the predominance of the former with intensities varying according to the selected technology and the climatic zone. Ihara et al. [30] analysed countermeasures to the UHI and benefits to the energy performance of office buildings using annual meteorological and building energy models for calculating the year-round environmental impacts. It was found that the use technologies based on an increase in albedo cause a reduction in the cooling demand but also an increase of heating demand, resulting in a null global impact on energy consumption. Furthermore, humidification and the

installation of heat sinks were calculated to reduce the energy consumption by 3% and 1% respectively. Similar analyses were carried for Tokyo, Japan, by Kikegawa et al. [31], who concluded that heat-island countermeasures allow a reduction by 0.2–1.2 °C of the air temperature in summer and consequently a reduction of cooling energy-savings between 5% and 20% depending on the type of countermeasure. Based on previous studies, the potential of mitigation strategies for several aspects, including energy consumptions was assessed by Sailor and Dietsch [32]. Kikegawa et al. [33] developed a numerical simulation model, in which a set of UHI countermeasures were applied to a central business district in Tokyo. Simulations showed that the anthropogenic heat reduction from air-conditioning facilities can produce up to 6% of cooling energy savings and a decrease of about 1 °C in the urban canopy during summer.

The analysis of the variability of cooling climatic indicators at urban level started more than two decades ago [34]. The need of climatic indicators at city scale was addressed by Kohler et al. [35], who developed a new degree-day method in which air temperatures and building energy demands are directly outputted from a regional urban meteorological model (non-hydrostatic regional Weather and Research Forecasting model) that takes into account both inter-building effects and UHI. Nik [36] developed a method based on synthesising three sets of weather data (two extremes and one typical) from a regional climate data set with the aim of decreasing the number of weather data sets without losing the quality and details of the original future climate scenarios. Advanced solutions may provide more detailed data for proper planning, as the use of satellite observation and big data technology for the analysis of urban temperatures [37,38].

Starting from the assumption that climate conditions, building energy performance and urban layout are strictly related to each other, many recent studies have also demonstrated the need of mapping building energy use at the urban scale instead of building level. Li et al. [39] and Frayssinet et al. [40] carried out reviews of the broad categories of energy models for urban buildings available in the literature. In [39] energy models at city level are grouped in two categories: bottom-up physics-based approaches, which analyse and simulate detailed energy demand and end-use services of buildings, and top-down approaches based on the long-term analysis of the relationship between energy consumption and economic indicators [41,42]. Examples of bottom-up methods are the following. Chen et al. [43] developed a new open web-based tool for city-level building energy assessment, using EnergyPlus as energy calculation engine and relying on cities' datasets (building technologies, utility data, etc.) and user-selected energy conservation measures for improving the building performance. GIS data sources are used to create the building dataset, but the energy calculation is based on Typical Meteorological Year 3 (TMY3) weather files. Robinson et al. [44] presented a new software called "CitySim" for building energy simulation at district level and Quan et al. [45] developed a GIS-based urban building energy modelling system which includes building information, mutual shading, microclimate and occupant behavior as input data for building energy performance calculations. Both papers do give high importance to the accurate modelling of the operational energy use of buildings at urban scale, but also in these cases, climate information are provided as single input. On the other side, examples of top-up approaches were developed by Zhang [46] and Summerfield et al. [47]. In both cases, weather/climatic conditions were incorporated in the model and put in relation with building energy consumption and economic expenses at city or region scales but, similarly to the bottom-up approaches, meteorological data were taken from urban or even regional database. Summarizing, in the analysed literature on the impact of UHI on building energy needs, the spatial variability within the city of the climate parameters and the influence of the urban texture on ambient temperatures is not considered.

2. Aim and methodology

The literature review evidences some limitations and critical aspects related to the investigated topic, in particular:

- Many studies are based on measured data with spatial or temporal limitations. In the first case, long data series by an urban and a rural station are used to assess the temporal trend of the UHI intensity, trying to detect possible impacts of climate changes. However, the impact of the urban pattern on temperature is not assessed. In the second case, the influence of the layout of the city (building density, streets dimension, vegetation, building characteristics) is taken into account by stations located in different zones of the city, but with measurement campaigns of short lifespan: it prevents UHI seasonal analyses as a function of seasonal thermal levels. Such limitations are, obviously, observed in cases of studies with limited temporal and spatial evolution of UHI.
- An important issue is the installation of monitoring stations. Microclimatic quantities are frequently measured with sensors placed above the urban canopy layer. This configuration affects the accuracy the calculation of the building energy performance, whose thermal response is mainly dependent on the microclimatic conditions within the urban canyon.
- Several studies and models address the performance of buildings and energy systems at district or city scale. Air temperature, however, is often seen as a single input, based on reference data, generally measured out of the city belt, or by a single station. Hence, the spatial variability is neglected, affecting the accuracy of predictions.

In this framework, the aim of this paper is a comprehensive assessment of the spatial and temporal evolution of the urban temperature and its impact on the energy performance of buildings. The purpose is to accurately address two crucial urban energy-related topics:

- a reliable prediction of buildings' energy performance in their effective microclimate conditions
- the need for realistic reference climatic datasets in building-related energy policies and standards, taking into account the UHI.

More in detail, this study is aimed at pursuing two main objectives:

(a) First, the spatial and temporal evolution of the urban climate in the city of Rome is assessed through continuous monitoring of the air temperature and relative humidity in selected neighbourhoods, which are representative of the diversity of urban textures in Rome. The urban heat island phenomenon is therefore quantified.
(b) Second, the monitoring data are used as input for building energy simulations to quantify the impact of the urban climate on the energy performance of buildings, with regard to the climatic dependent energy uses for space heating and cooling. Two main building categories are considered: residential and office. Aspects related to not cooled buildings are addressed in [48].

Rome is the capital of Italy, with a surface area of 1287 km^2 and 2.87 million residents and a total of more than 3 million usual residents, namely including those people who live or work in Rome without being formally resident. The population of the whole metropolitan area (5352 km^2) exceeds 4.36 million people. Rome is a green city with two third of the municipality area consisting of listed environmental area, often connected with historical and archaeological sites [49]. These areas, however, are peripheral and figures change looking inside the city: Rome, scoring 3.5%, holds the 39th place in the country for the urban green area density, expressed as the ratio of green area on the municipality surface [50].

The urban texture in Roma is articulated: the core of the city is densely built and low vegetated; moving out from the city centre,

heavily constructed zones alternate to un-built and green areas. Being the history of the city close to three millennia, the characteristics of the building stock are extremely variegated regarding urban layout, age, geometry and size, and construction technologies. Since a capillary climatic monitoring was not possible due to the scarce availability of resources, it was decided to investigate four exemplary areas: city centre zone (CCZ); a semi-peripheral zone built in early 20th century (SP1); a more recent semi-peripheral zone, with deeply different urban layout (SP2); a peripheral zone (PE). Aerial views of the investigated zones are presented in Fig. 1, while Table 1 summarizes the most relevant characteristics of the selected climatic zones. In Table 1 the H/W ratio represents the ratio of the canyon height (H) to canyon width (W), H/W, which is defined as the aspect ratio. The urban climate is compared to a rural area (RE), used as a reference case for the UHI assessment and analysis. This site is located 11 km west of the city centre, halfway to the Tyrrhenian Sea. Being west the prevalent wind direction in Rome, the reference site results undisturbed by the UHI effect.

Air temperature and relative humidity are measured in the five different sites, and collected data are analysed for winter and summer, observing differences among zones in terms of temperature average, profiles and relevant climatic indicators. The dataset used for this analysis refers to 3 years from October 2014 until September 2017. In the next phase, the datasets are used as input to perform energy simulations of building in transient regime. Cooling and heating energy performance are calculated for two reference case studies (residential and office buildings) ideally located in the selected neighbourhoods. To be noted that a single reference solar irradiation dataset was used for all the zones, being this quantity constant in the area considered for the numerical analysis. This analysis allows quantifying the impact of urban climate on heating savings and cooling penalties of buildings, as well as to advice about risks of inaccurate thermal and climate predictions.

The implemented methodology, as previously described, introduces elements of novelty aimed at filling gaps for what concern the interaction between the urban environment and its impact on buildings' and, more in general, energy systems' performances, as documented in the review of existing studies.

3. Field measurements

The study started in June 2014, when the microclimatic stations were mounted in the four selected neighbourhoods. They were placed at 4–6 m from the ground and under the canopy. Each station consists of a battery-powered self-standing data logger, and a radiation-shielded air temperature and relative humidity sensor, whose main characteristics are:

- 0.1 °C temperature resolution in the −40 °C–82 °C range;
- ± 0.5 °C maximum temperature error in the −5 °C–60 °C range;
- 0.1% humidity resolution in the 0–100% range
- ± 5% maximum humidity error in the 10–100% range.

Measurements were acquired every 10 min, even if different average time steps were used for the analysis and calculations following presented.

The micrometeorological station of Castel di Guido belonging to the network of the Environment Protection Agency of Lazio Region was used as a reference. Technical specifications of the measuring equipment can be found in [51]. Air temperature and relative humidity were provided for the June 2014 – September 2017 period with a time resolution of 30 min. The dataset presented a limited number of gaps, infilled by interpolation or with data provided by a nearby station.

4. Numerical analysis

The numerical analysis was developed using the software TRNSYS, a well-known and flexible tool, able to simulate the thermal behaviour of the building in the transient state [52]. TRNSYS works with assembled calculation components, each of which having a specific task and modelling the performance of one part of the system. The project implemented in the current paper consists of the following components: weather data block, which includes the climatic data acquired through

Fig. 1. Aerial view of the monitoring zones of the City.

Table 1
Main characteristics of the selected Rome neighbourhoods.

Site station	Urban density	Urban pattern	Main building typology	Building Age	Vegetation	Pavements	H/W in the monitored street
CC	High	Irregular with narrow streets having an average width of 8–10 m. Main roads are about 20 m width	Court and massive building	From Middle Age to late 19th century	Absent; few private gardens	Basalt stone	2.2
SP1	High	Regular with narrow streets having an average width of 10–15 m. Main roads are about 25 m width	Isolated apartment blocks	Early 20th century	Private residential gardens and trees on streets	Asphalt	1.3
SP2	Medium	Irregular with medium-large streets having an average width of 15–20 m. Main roads are about 60 m width	High rise blocks	Different decades of 20th century	Trees on streets and small public parks	Asphalt	0.4
PE	Medium	Regular with narrow streets 8–10 m. Main roads are about 20 m	Isolated apartment blocks	Middle of 20th century	Private residential gardens and big public parks	Asphalt	2.6

the microclimatic stations; the solar generator which allows to build the solar irradiation dataset; additional components used for specific calculation tasks (such as the calculation of the effective sky temperature and of the heat transfer through the ground); the building block, which is filled in with all the data building inputs; the output component which gives the results of the calculation. The two buildings used as reference case studies in this paper are a four-floor apartment block, which represents one of the most common building type in Italy, and a typical building office.

Each floor of the building is occupied by two apartments and all of them have three external façades. The main geometric data of each apartment are: net floor area 89.7 m^2, net volume 242 m^3, windows area 13.6 m^2. The windows surface is uniformly distributed on the facades, without introducing selectivity criteria according to the orientation; moreover, the window surface account to 15% of the apartment net floor area, as general design criteria in Italian dwellings.

The office building is facing north and south and has no external obstructions; it has a rectangular plan and consists of four floors of 3 m height. The main geometrical data of the building are shown in Table 2. The plans of the apartment block and office building are shown in Figs. 2 and 3 The simulations on both the buildings are carried out considering two envelope configurations: without thermal insulation, representative of existing buildings, and insulated, representative of new or renovated buildings. U-values of the components are shown in Table 3. For the non-insulated configuration, representative values of typical construction technologies are chosen, while the values for the insulated buildings are based on the national building code [3].

In the residential building, internal gains are set to 5 W/m^2 of sensible heat and 2.5 W/m^2 of latent heat according to Italian standard reference [53]. Windows are equipped with external solar protection devices, activated only during the cooling season and with a shading coefficient of 0.8. Both the heating and cooling seasons are taken into account in the simulation: the air temperature set-point is 20 °C in the winter season, and it is 26 °C in summer. The set-point of relative humidity in the cooling season is 60%. The calculation is carried out considering an operation schedule of the energy system: in the heating season the system is on from 6:00 to 10:00 and from 15:00 to 23:00; in the cooling season it is on from 10:00 am to 23:00. Natural ventilation is considered with 0.3 air exchange per hour.

In the office building, internal gains (people, equipment, lighting) in working spaces follow the schedule shown in Table 4, while in the service spaces (corridors, toilets and stairs) the value is set to 3 W/m^2. A fixed air exchange of 30 m^3/h per person is considered, and in every single office there are 1.5 people. The energy system operation is 07–18 both in cooling and heating seasons; when the office is closed a fixed value of 0.15 air exchange per hour is considered for air infiltrations.

In this paper, the net energy used is calculated, namely the energy needed to keep the building zones at the set-point values without taking into account the efficiency of the installed energy system. This approach was preferred since the main target of this study is to assess the thermal response of the two buildings under different external conditions.

5. Results

5.1. Urban monitoring

This section is dedicated to the presentation of the monitoring results, with the comparison of the urban climate and the rural condition. The first exemplary effect can be observed in Fig. 4, where the hourly UHI values in the selected zones are plotted for five days of July 2016. It can be seen that temperature increases differently according to time and space: peaks change in the four urban zones, depending on the specific characteristics of the area, and differences between maximum and minimum values have a magnitude of several degrees, e.g. close to 7 °C in SP2. The plots show that UHI reaches its peak during the central

Table 2
Geometrical data of the building.

Thermal zones	Floors	Floor-Floor height (m)	Window Area (m^2)	Total window area of each floor (m^2)				Total wall area of each floor (m^2)				Gross floor area (m^2)	Volume (m^3)
				N	S	E	O	N	S	E	O		
Offices-North	4	3	4.06	53	0	0	0	130	0	84	84	167	501
Corridors and toilets				8	3	0	0	19	8	5	5	105	378
Offices-South				0	53	0	0	0	130	84	84	188	552

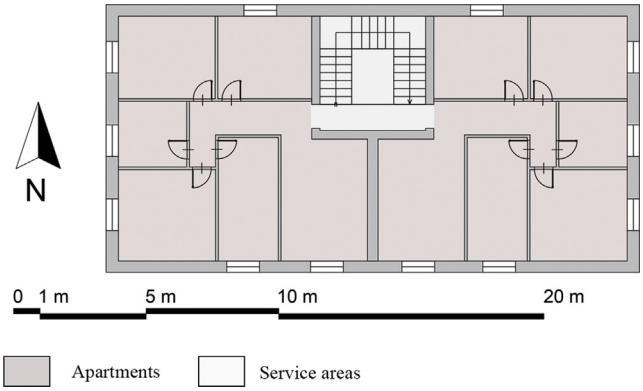

Fig. 2. Residential building plan.

Table 3
U-values of building components.

Building configuration	U-roofs [$W/m^2 K$]	U-wall [$W/m^2 K$]	U-ground [$W/m^2 K$]	U-window [$W/m^2 K$]
Not insulated	0.99	0.96	1.14	5.68
Insulated	0.26	0.29	0.29	1.80

Table 4
Schedule of internal gains in office building.

Weekday hours	9	10	11	12	13	14	15	16	17	18-2
Internal gains [W/m^2]	22	22	22	12	12	22	22	22	22	2

part of the day but remains high during the night time, going to a minimum in the early morning hours.

Regarding the aggregated data, the heating and cooling degree days are relevant indicators to characterise the climate of a territory and to assess the energy performance of buildings. According to the space heating and cooling set-points fixed by the national building code [53], heating degree days (HDD) are calculated based on a reference value of 20 °C and cooling degree days (CDD) based on 26 °C. Being the objective of this paper to explore in detail the urban climate, the indicators are calculated for the whole year, without taking into account the national building code requirements. Table 5 presents the absolute annual values, calculated as the average of the three-year observation period. HDDs in the reference station are 1836, while the average of the urban stations is 1540. It has to be noted that the four stations measured very close values (the maximum difference is 64 HDDs) and the impact of urban climate is an HDD decrease ranging between 14% in the peripheral zones and 18% in CCZ. As expected, much lower values are calculated for CDDs, being 101 in the reference station and an average of 236 in the urban areas. In this case, the results are more scattered, with peak deviation of 59 CDDs between the two extreme zones. With lower quantities, variations are much higher; maximum increase in CCZ is about 157%, and the minimum in PE is 109%.

Concerning UHI, a first analysis is the dependence of this indicator on the absolute temperature values. As an exemplary case, in Fig. 5 the average summer UHI values are plotted against the average summer air temperature of the reference station; data refer to the four monitored neighbourhoods and include the year 2014, for which only data starting from late June were available. According to the figure, UHI is a horizontal line, and deviations do not follow the fluctuations of the ambient temperature. It can be thus stated the UHI does not depend on absolute temperature levels.

Hourly urban heat island intensities resulted almost identical for the

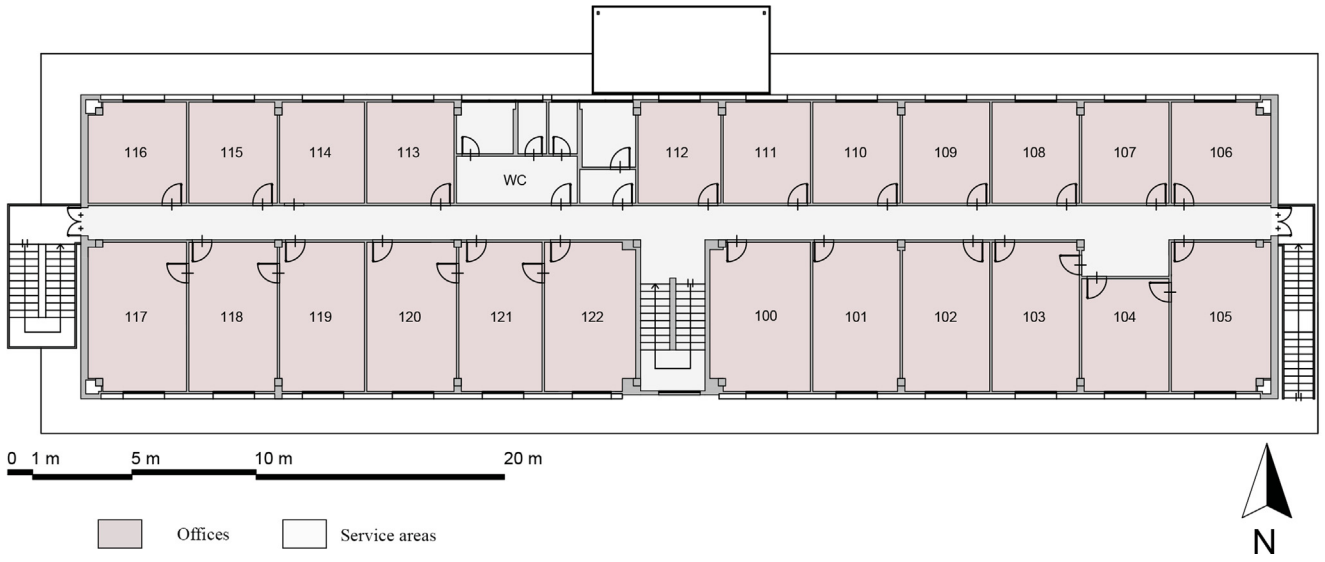

Fig. 3. Office building plan.

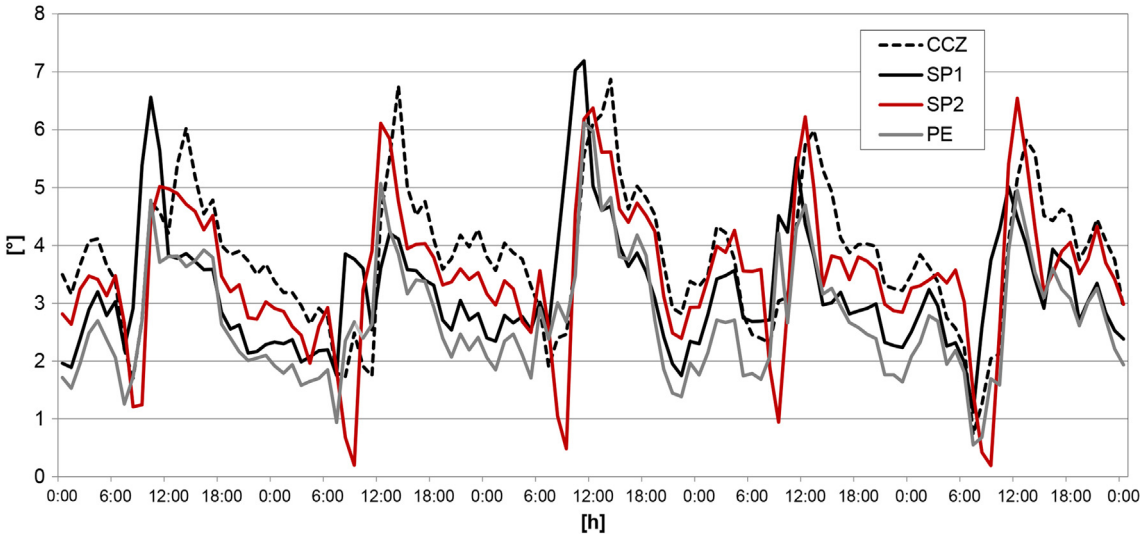

Fig. 4. Hourly UHI in the urban stations in 5 days during July 2016. CCZ is the city centre zone, SP1 the ancient semi-peripheral; SP2 the more recent semi-peripheral zone; PE the peripheral zone.

Table 5
Heating and cooling degree days in the monitored zones.

	RE	CCZ	SP1	SP2	PE
HDD (°C day)	1836	1508	1538	1544	1572
HDD Relative decrease (%)	–	18	16	16	14
CDD (20°) (°C day)	101	260	227	247	211
CDD Relative increase (%)	–	157	125	145	109

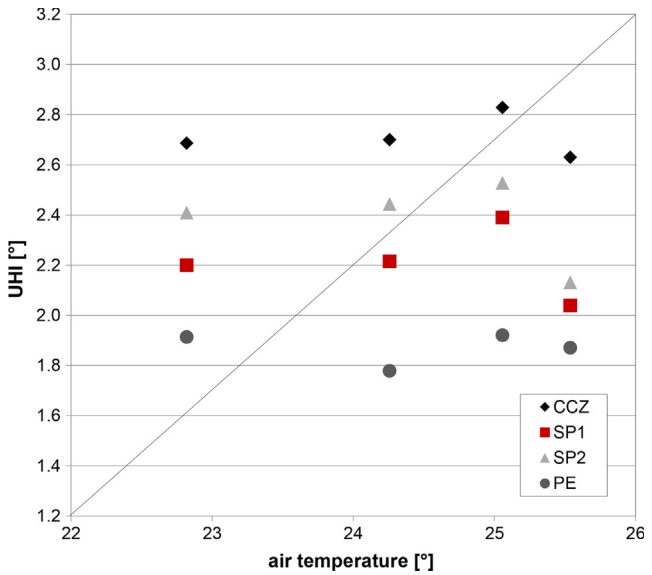

Fig. 5. Average summer UHI values plotted against the average summer air temperature of the reference station.

four zones, varying between 8.3 and 8.4 °C. The data were analysed for summer (May 15-September1 5) and winter (December 1-March 31), taking into account the warmest and coldest seasons, on a 4-month basis. To be noted that in winter, the year refers to the final date of the season. Table 6 summarises average seasonal UHI values for the three monitored years. Results show that UHI is quite uniform through the city in winter, being the variation among zones in the 0.1 °C range for the whole period and 0.2 °C for a single year. Conversely, UHI in summer is more influenced by the different urban zones. CCZ is the warmest zone with an average UHI of 2.7 °C, which decreases to 1.9 in PE. The two semi-peripheral zones fall in the middle, with UHI values of 2.2 and 2.4 °C for respectively SP1 and SP2. Average UHI variations among zone reach 0.9 °C in summer. The average UHI values for the whole three years, also including the intermediate seasons, is well aligned with the seasonal values, showing a clear reduction of PE compared to the other urban zones.

Aggregated data, however, do not provide insights about the characteristics of the urban temperature evolution, thus also disaggregated data are provided. Fig. 6 shows the frequency distribution of the hourly UHI in summer. In CCZ the highest frequency of UHI is in the 2–3 °C range, which is reached in 25% of the period, but also the frequency of 3–4 °C is very high (23%); the area is the most affected by UHI as demonstrated by values above 6 °C in 6% of the period and above 3 °C in 45% of the period. The two semi-peripheral neighbourhoods show a similar thermal response: in both cases the highest UHI frequency is between 2 and 3 °C, being reached in 33% and 28% of the hours for respectively SP1 and SP2. The latter is also affected by extreme conditions, in fact UHI between 4 and 6 °C is reached during 13% of the period, respect to the 8% calculated for SP1. PE is by far the coolest area, in fact most recurrent UHI range is between 1 and 2 °C (31% of the period) and it is below 3 °C in the 80% of the monitoring period. It is also relevant to note that all the selected zones are affected also by urban cool island (UCI) during the period. The magnitude is not negligible, ranging in the same range for all the zones (7–8%): the origin of the phenomenon should be imputed to the masking and shadowing

Table 6
Average UHI values during the monitoring period.

	UHI [°C]			
	CCZ	SP1	SP2	PE
	Summer			
2015	2.8	2.4	2.5	1.9
2016	2.7	2.2	2.4	1.9
2017	2.6	2.0	2.1	1.8
Average	2.7	2.2	2.4	1.9
	Winter			
2015	1.0	0.9	0.9	0.8
2016	0.7	0.7	0.7	0.6
2017	0.7	0.6	0.6	0.7
Average	0.8	0.8	0.7	0.7
3 years average	1.7	1.5	1.6	1.2

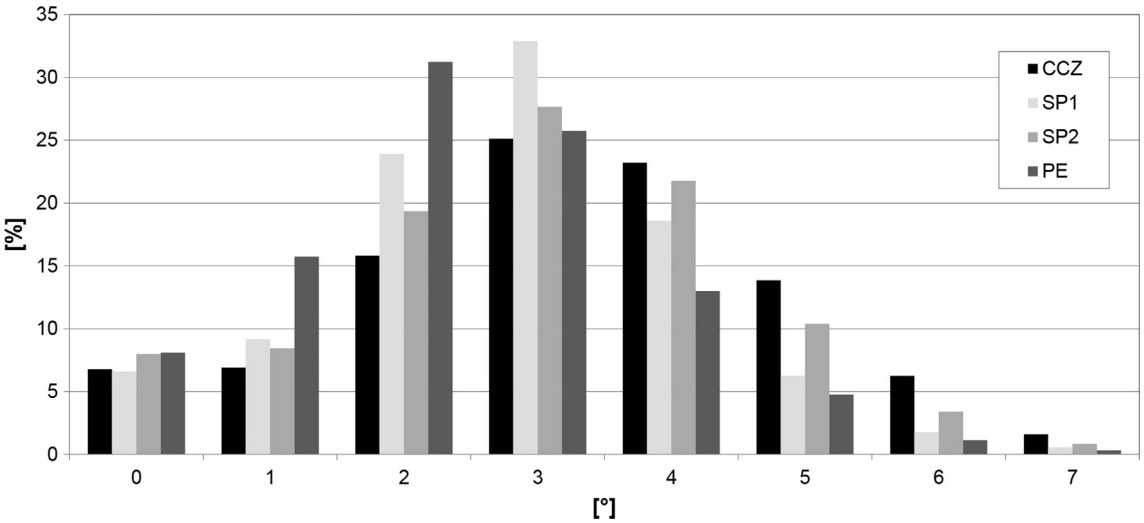

Fig. 6. Frequency distribution of hourly UHIs during summer.

effect of urban fabrics which delay the warming effect of the solar radiation in urban canyons respect to the open fields of the rural station. This is confirmed by the fact all the UCI hours are in the three hours between 6.00 and 9.00 in the morning.

In winter the trends are similar to those during the summer, but the absolute figures significantly do change (Fig. 7). CCZ has more than 40% of the hours with UHI between 2 and 3 °C, resulting again the area most affected by the phenomenon. PE is slightly affected by UHI in winter; in fact, the ambient temperature in PE exceeds by 1 °C the value at the reference station only in 32% of the hours. In SP1 the highest frequency is registered for UHI between 1 and 2 °C with 55% of the hours; only in 5% of the hours UHI rises above 2 °C. Anomalous results are instead achieved for the SP2 station, in fact, the zone is in UCI conditions for half of the period and the highest UHI frequency is obtained for the 0–1 °C interval (23°); however, the UHI hours above 2 °C are 9%, almost the double of SP1. Relevant UCI conditions are also calculated for the other zones, ranging between 11% in SP1 and 20% in PE. The unusual UCI conditions registered for SP2 can be imputed to the wide boulevard with tall trees and the relative proximity of Tiber river: these aspects create favourable conditions for cooling down the zone, especially at night time. In addition, the limited irradiation availability in the reference station in early morning hours have an impact on UCI conditions for SP2. To be noted that, in full accordance with average figures, the frequency distribution shows how the UHI is more intense in summer.

A last relevant issue is the assessment of UHI as a mainly nocturnal or diurnal phenomenon. In summer the daytime is calculated for the 8.00 to 18.00 (no energy saving time considered) and night time from 21.00 to 6.00 of the next morning; in winter diurnal hours go from 8.00 to 16.00 and nocturnal hours from 19.00 to 6.00 of the next morning. Aggregate results are presented in Table 7 and refer to the three years period; it shows significant differences depending on the urban zones and the season. In CCZ there is no significant variation between nocturnal and diurnal UHI in summer; the cause might be found in the small ratio between width of the street and height of the buildings which create favourable conditions of the heat entrapment under the canopy and thus a more difficult radiative cooling at night. Higher differences are measured for the other zones, ranging in the 0.3–0.4 °C range, showing the UHI is mainly a diurnal phenomenon in Rome. Mixed up results are obtained for the winter case. In CCZ the UHI is typically nocturnal (0.8 °C higher), while in SP2 is typically diurnal (0.7 °C higher); the reason for the latter is the same discussed above, while for CCZ causes should be searched in limited solar gains and a mainly anthropogenic heat driven UHI in winter. A trend similar to CCZ but less intense is observed in SP1, and the nocturnal UHI is 0.3 °C higher than the diurnal one; in this case, also the geometry of the

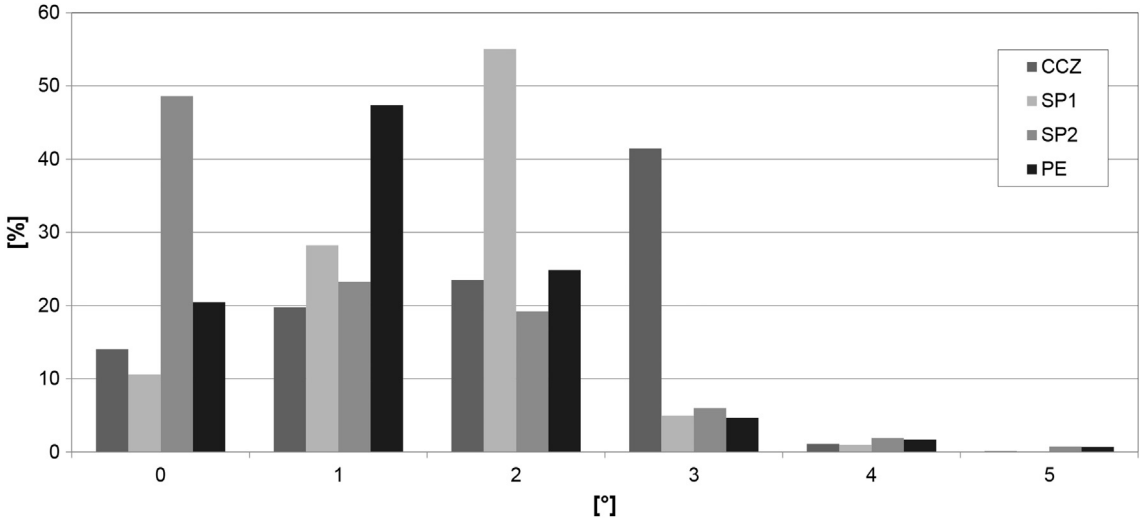

Fig. 7. Frequency distribution of hourly UHIs during winter.

Table 7
Nocturnal and diurnal average UHI.

	Hours	UHI [°C]			
		CCZ	SP1	SP2	PE
		Summer			
daytime	8.00–18.00	2.7	2.4	2.6	2.1
night	21.00–06.00	2.8	2.1	2.2	1.7
		Winter			
daytime	8.00–16.00	0.3	0.6	1.2	0.8
night	19.00–6.00	1.1	0.9	0.5	0.7

buildings plays a relevant role. No significant excursions are instead observed for PE.

The cumulative distribution of UHI during daytime and nighttime is shown in Figs. 8 and 9, where diurnal and nocturnal plots are presented for respectively CCZ/SP1 and SP1/PE. Results are shown for the summer season, the most affected by UHI. Diurnal UHI values above 4 °C are obtained in 17% of the period in CCZ, while the value decreases to 7% at night. The extreme values are different, but figures are similar for less intense situations: UHI below 2 °C is calculated in 59% and 56% of the hours respectively during daytime and night time. A similar trend is found in SP1: UHI above 3 °C is calculated for 23% of the period during daytime and 11% at night. An inversion with respect to CCZ is found for UHI below 2 °C: diurnal share accounts for 58% and nocturnal is higher with 65%. SP2 is aligned with CCZ for the extreme values, with UHI intensity above 4 °C in 16% of daytime and 4% of night time. This zone is the most affected by UHI during the daytime. PE zone takes advantage of night cooling. In fact, the nocturnal UHI is above 3 °C only in 7% of the hours, and it is below 2 °C in 75% of the period; same share (57%) of UHI above 1 °C is obtained for daytime and night.

The impact of urban climate on air relative humidity was, finally, analysed. Concerning the winter season, average values for the three years show that differences are close the negligible; the relative humidity ranges between 69% in CCZ and 72% in PE. The trend is also observed in terms of cumulative distribution: the number of hours above 50% and 70% are in the 88–89% and 55–89% range, respectively. Results for the summer season are slightly different; the average value of the reference station is 66%, CCZ humidity is 56% and the other three zones 68%; the trend is also confirmed by observation of cumulative distribution occurrence. To be noted that relative differences among zones are observed on an annual basis, even if with absolute values changing according to the single year. According to these results, it can be stated that the impact of urban climate on air relative humidity is not significant, even if in summer a slight positive reduction of air relative humidity is observed.

5.2. Building energy performance

The impact of the urban climate on the energy performance of the two reference buildings was calculated, using the datasets consisting of the hourly values of air temperature and relative humidity, collected during the monitoring period. The results of the heating and cooling energy uses for the five selected zones, the three years dataset and for both insulated and non-insulated building configurations are presented in Table 8 and 9. Relative variation of cooling and heating energy uses respect to the reference station are presented in Figs. 10 and 11. The calculation was carried out for the whole year, without taking into account pre-defined heating and cooling season. To be noted that the heating energy use of 2015 refers to the winter period from 1st December 2014 to 31st March 2015. A first observation is about the variability of climatic conditions among the monitoring years, which leads to variations up to 11 kWh/m^2 for a specific energy service; for simplicity, the results are following presented as the average of the three years observation period. A second evident observation is that UHI leads to a decrease of heating uses and an increase of cooling use in the urban environment. However, energy performances follow different path according to the season and to the building characteristics (see Table 9).

Concerning the non-insulated residential building, the reference station registers 24 and 21 kWh/m^2 for respectively net space heating and cooling. The heating uses uniformly decreased to 19 kWh/m^2 in all the zones of the city with 20% average relative reduction. Results are zone depending for cooling uses, ranging from 32 (PE) to 37 (CCZ) kWh/m^2, in relative terms, these figures correspond to an energy increase between 52 and 76%. This strong variation depends mainly on the reduced solar gains due to the solar protection devices of glazing systems and on the relatively low internal gains, which make the building more sensitive to external temperature variations. The

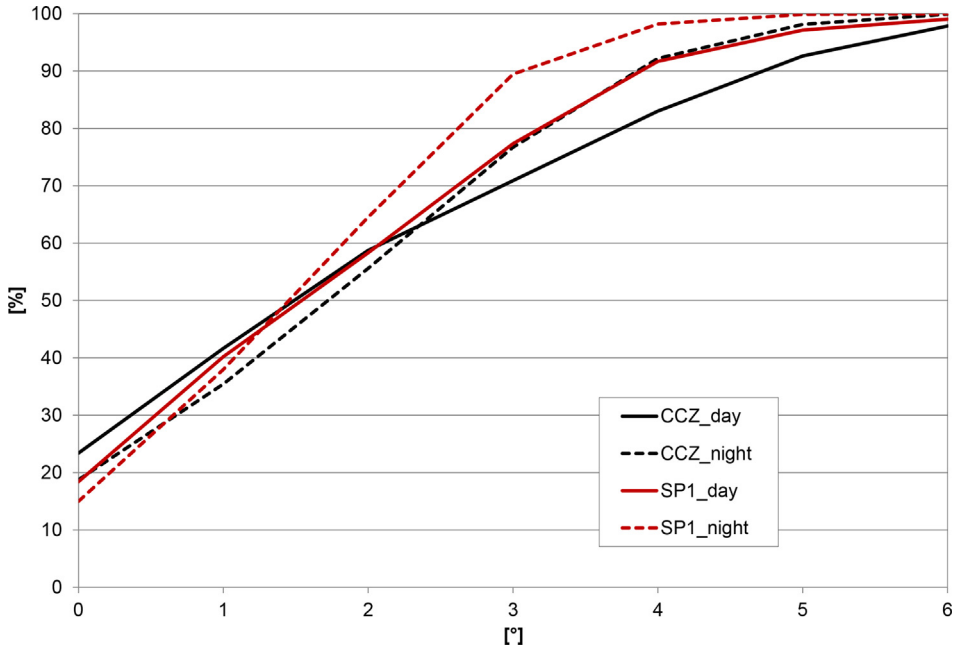

Fig. 8. Cumulative distribution of nocturnal and diurnal UHI in CCZ and SP1.

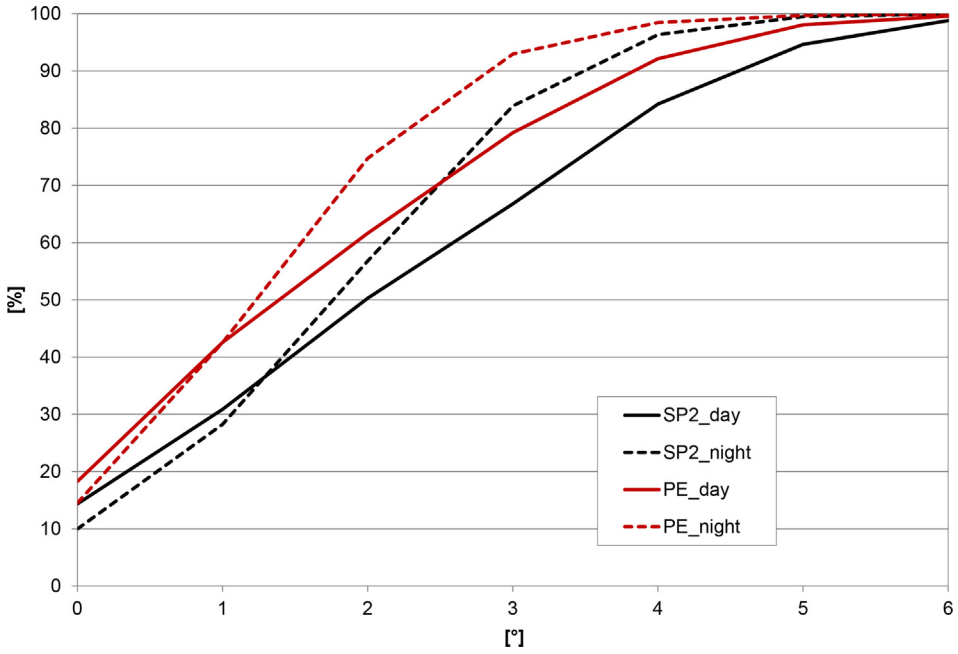

Fig. 9. Cumulative distribution of nocturnal and diurnal UHI in SP2 and PE.

Table 8
Results of the energy uses in the residential building.

Residential building											
Type	Year	CCZ		SP1		SP2		PE		RE	
		Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)
Not insulated	2015	19	40	19	38	20	39	20	35	26	24
	2016	16	32	15	29	17	31	16	27	20	17
	2017	23	38	23	35	22	36	22	33	27	23
Average		19	37	19	34	19	35	19	32	24	21
Insulated	2015	2	30	2	28	2	29	2	27	2	20
	2016	2	27	2	26	2	27	2	24	2	18
	2017	2	26	2	24	2	25	2	23	2	17
Average		2	28	2	26	2	27	2	25	2	18
Δ ins/non-ins		91	25	91	23	91	23	91	22	93	15

Table 9
Results of the energy uses in the office building.

Office building											
Type	Year	CCZ		SP1		SP2		PE		RE	
		Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)
Not insulated	2015	23	61	24	58	23	60	25	54	31	40
	2016	20	52	20	49	20	51	20	46	24	33
	2017	28	57	27	53	28	53	27	51	32	39
Average		24	57	24	53	24	55	24	51	29	37
Insulated	2015	2	74	2	72	2	73	2	70	3	60
	2016	2	71	2	69	2	71	2	68	2	58
	2017	3	63	3	61	3	62	3	60	3	52
Average		3	69	2	68	3	69	2	66	3	57
Δ ins/non-ins		89	−23	90	−27	89	−26	90	−30	91	−53

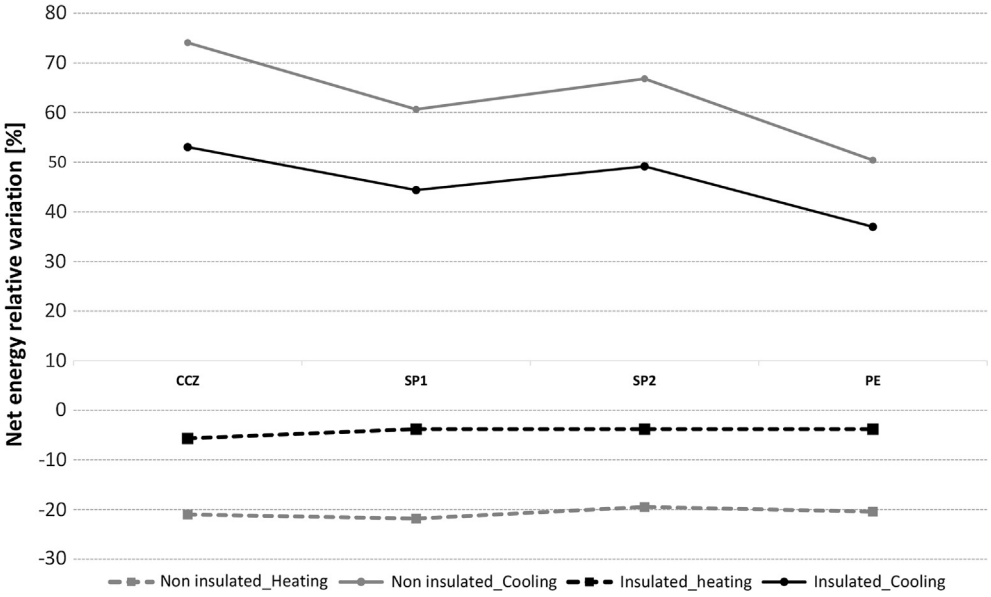

Fig. 10. Relative variation of heating and cooling uses of the residential building in different neighbourhoods respect to the reference station.

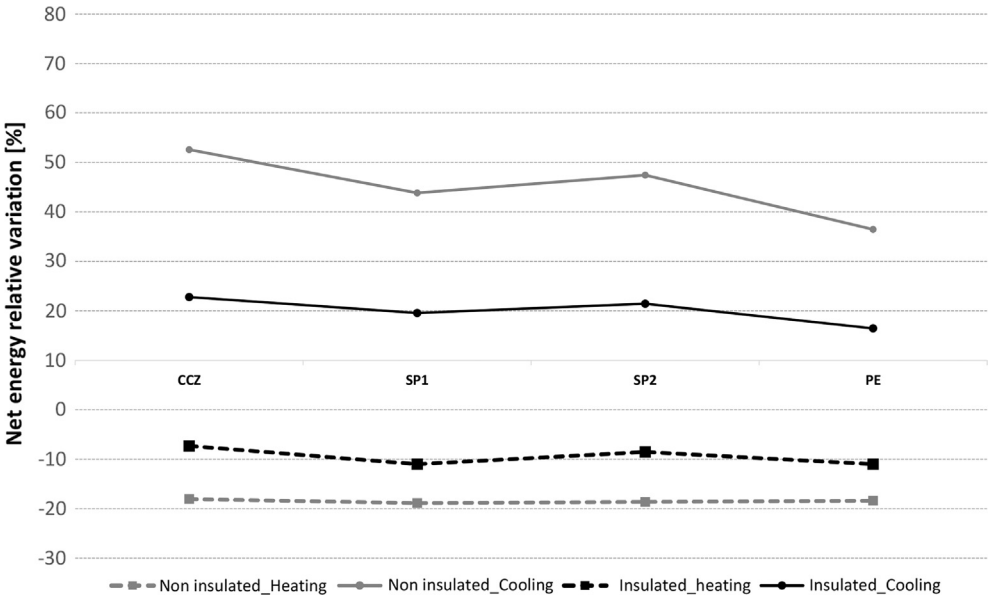

Fig. 11. Relative variation of heating and cooling uses of the office building in different neighbourhoods respect to the reference station.

Table 10
Impact of UHI on cooling energy performances of the reference buildings.

Building typology	Cooling variaton (kWh/m^2°C$_{UHI}$)	Relative cooling variaton (%/°C$_{UHI}$)
Residential not_ins	4.9 ± 0.1	25.0 ± 0.5
Residential_ins	2.3 ± 0.1	17.6 ± 0.2
Office not_ins	5.6 ± 0.1	18.0 ± 0.4
Office ins	3.1 ± 0.1	23.8 ± 0.5

magnitude of the results significantly change for the net space energy uses in the insulated residential building. The high thermal resistance of the envelope elements, as well as the high solar gains, ensure minimum energy need in all the zones (about 2 kWh/m^2), relative reductions are in the 5% range, but cannot be considered significant because of the very low absolute values. Net cooling uses follow the same trend observed for the not insulated building with lower figures due to the increased insulation levels: 18 kWh/m^2 are calculated for the reference station, while the urban stations range between 25 (PE) and 28 (CCZ) kWh/m^2. The associated relative variations range between 40% and 55%.

Concerning the non-insulated office building, the reference station registers 29 and 37 kWh/m^2 for respectively net space heating and cooling; this is a noticeable difference respect to the previous case since cooling uses are higher than heating one already in the not insulated configuration. The net space heating reduction is uniform in the four urban zones and accounts for 5 kWh/m^2, about 17% in relative terms. Cooling results are, instead, neighbourhood dependent with cooling uses ranging between 51 (PE) and 57 (CCZ) kWh/m^2, the corresponding relative variations are in the 38–54%, well aligned with the insulated residential building. Space heating performances of the insulated building are very similar to those calculated for the equivalent residential one: reductions are in the 10% order. However, absolute values are very small (3 kWh/m^2) to be considered significant for an urban climate-related analysis. Conversely, net cooling uses increase up to 57 kWh/m^2 in the reference zone and reach the maximum in CCZ

with 69 kWh/m^2, the peripheral neighbourhood remains the least affected by UHI, and the cooling use is 66 kWh/m^2. The relative variations are smaller for this building configuration and range between 16% and 21%, depending on the fact that this building configuration creates favourable conditions for overheating.

This aspect is worthy of investigation and can be evidenced looking at the different response of the two building typologies as a consequence of the increased thermal insulation. The insulated office building, despite the well performing solar shading, still has relevant solar gains, as well as high internal gains due to the installed equipment; these loads determine a strong warm-up of the building structure during the day that cannot be dissipated at night without dedicated strategies (e.g. night ventilation cooling). The impact is relevant: the cooling use of the office building raises from 37 to 57 kWh/m^2, with 54% relative variation. To be noted that the relative variation ranges from 20% to 30% in urban stations, since the not insulated building is more sensitive to higher temperatures. Different performances are detected for the apartment building, the effect of insulation is, in fact, a reduction of cooling used from 21 to 18 kWh/m^2, corresponding to 14% in relative terms. The effect is more positive in the urban environment with an average relative reduction of cooling uses between 22% and 24% (PE), for respectively SP2 and PE, due to the heat barrier of the insulated envelope in buildings with low solar and internal gains.

An important indicator to assess the thermal response of building in the urban environment is the space heating and cooling variation per UHI degree. This indicator was calculated for the winter and summer period as indicated in Section 5.1. The energy reduction for space heating for the not insulated residential building ranged between 5.4 (SP2) and 6.2 (PE) kWm^2/year per each UHI degree, with 26% average in relative terms; for the not insulated office building such reduction ranged between 4.9 (CCZ) and 6.1 (PE) kWm^2/year per each UHI degree, with 22% average in relative terms. This calculation was not carried out for the insulated buildings, due to the very low space heating demand. The results of the cooling season are presented in Table 10. Concerning the absolute variations among zones, it can be noted that they are more uniform than those detected for the space heating analysis (± 0.1 kW/m^2°C$_{_UHI}$), conversely there is a significant dependence on the building typology: difference ranges between 2.3 (insulated residential building) and 5.6 (not insulated office building) kWm^2/year per each UHI degree. Relative variations range between 17.6% and 25% kWm^2/year per each UHI degree for respectively the insulated and uninsulated residential building.

The last notation is about the impact of the latent heat for the cooling performances. It accounts for 11% of the total cooling uses of the apartment building in the reference station and about 8% for the urban stations, with variation in 1% range among the 4 zones; negligible variations are registered between the insulated and not insulated configurations. The incidence of latent heat is even lower for the office building: 3 and 5% in the reference station for respectively the insulated and not insulated envelope, and about 2%, as an average, for all the urban stations.

6. Conclusions

In this paper, the spatial and temporal evolution of the urban climate in Rome is analysed, through continuous monitoring of the air temperature and relative humidity in four selected neighbourhoods and a reference extra-urban station for three years. The selected sites are different in terms of position in the city, urban pattern and geometrical characteristics. Reference and urban climatic data then used as input for a calculation analysis, aimed at demonstrating the impact of urban climate on the energy performance of different building typologies.

The main findings of the research can be summarised as follows:

- Observation of the urban heat island and relevant microclimatic indicators. An evident urban heat island is observed through all the monitoring period. The phenomenon is mainly uniform in winter with small variation among zones, while in summer there is a closer dependence on the observed zones. Heating degree days decrease by 16–18%, and cooling degree days increase by 109–157%. Hourly urban heat island intensities raise above 8 °C in all the monitored neighbourhood. The average of the three years observation ranges between 1.2 °C in the outskirts and 1.7 °C in the CCZ.
- Temporal dependence. The phenomenon is more intense in summer than in winter; in fact, average values are 2.3 °C for the former and 0.75 °C for the latter; the maximum difference is observed in CCZ with 1.9 °C variation. Concerning the daily effect, it can be noted that in central zones there is a general increase of the phenomenon during the night, with an inversion moving towards the peripheral zones; however, no clear trends can be detected. To be noted that the size of the urban heat island is not dependent on absolute temperature level, as demonstrated by similar values measured in four summers (2014–2017) with significantly different air temperatures.
- Spatial dependence. Observing the 3 years averages, small differences are detected among neighbourhoods in winter (0.1 °C), with seasonal heat island values ranging between 0.7 and 0.8 °C in the selected zones. A different response is detected in summer, with seasonal variations of 0.8 °C among the zones. CCZ is the area most affected by the heat island, with seasonal average 2.7 °C, while the value decreases to 1.9 °C in the periphery. Intermediate values (2.2–2.4 °C) are observed for the semi-peripheral zones.
- Impact on building energy performance. According to different envelope configurations, the UHI reduces the space heating uses by 0.5–5 kWh/m^2 and increases the space cooling uses by 7–16 kWh/m^2 for the residential building in the different stations. For the office building, the heating reduction is 1–5 kWh/m^2 and the cooling reduction is 9–20 kWh/m^2. To be noted that the thermal insulation leads to a reduction of cooling uses in dwellings, while it causes an increase in commercial buildings. Regulatory prescriptions and building design, should hence properly address the issue of urban climate-related energy performance to optimise the energy performance of buildings by their use.
- Urban heat island normalised energy uses. The effect leads to average space heating reductions by 22% and 26% for each degree of urban heat island for the not insulated residential and office buildings. Concerning the cooling uses, an increase between 18% and 24% for each urban heat island degree is observed, depending on the insulation level and the building typology.

The present comprehensive study carried out for the city of Rome demonstrates the high variability of the urban heat island phenomenon, which seriously affects the energy performance of buildings. Long-term monitoring is needed to develop robust datasets, to be used in building energy-related policies, as well as in urban building energy analyses, where simplified input climatic data can lead to significant deviations respect to the real operation conditions.

Acknowledgements

Authors warmly thank Rossana Cintoli and Andrea Bolignano of ARPA Lazio (Regional Agency for Environment Protection) for kindly providing climatic data, crucial to carry out the present study.

References

[1] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.
[2] European Parliament. Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD recast). Official Journal of the European Union.
[3] Decreto del Ministero dello Sviluppo Economico del 26 giugno 2015. Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici.

[4] Palme M, Inostroza L, Villacreses G, Lobato-Cordero A, Carrasco C. From urban climate to energy consumption. Enhancing building performance simulation by including the urban heat island effect. Energy Build 2017;145:107–20.
[5] Rosenzweig C, Solecki W, Hammer SA, Mehrotra S. Cities lead the way in climate-change action. Nature 2010;467:909–11.
[6] Arnfield AJ. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol 2003;23:1–26.
[7] Santamouris M, Kolokotsa D. On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe. Energy Build 2015;98:125–33.
[8] Oke TR. City size and the urban heat island. Atmos Environ 1973;7:769–79.
[9] Stewart D. A systematic review and scientific critique of methodology in modern urban heat island literature. Int J Climatol, Special Issue: ICUC-7 Urban Climate Meeting; 2011; 31(2): p. 200–17.
[10] Allegrini J, Carmeliet J. Simulations of local heat islands in Zürich with coupled CFD and building energy models. Urban climate [in press], Available online 20 February 2017, https://doi.org/10.1016/j.uclim.2017.02.003.
[11] Cartalis C, Synodinou A, Proedrou M, Tsangrassoulis A, Santamouris M. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region. Energy Convers Manage 2001;42(14):1647–56.
[12] Lam TNT, Wan KWK, Wong SL, Lam JC. Impact of climate change on commercial sector air conditioning energy consumption in subtropical Hong Kong. Appl Energy 2010;87:2321–7.
[13] Ahmed T, Muttaqi KM, Agalgaonkar AP. Climate change impacts on electricity demand in the State of New South Wales, Australia. Appl Energy 2012;98:376–83.
[14] Santamouris M. On the energy impact of urban heat island and global warming on buildings. Energy Build 2014;82:100–13.
[15] Radhi H, Sharples S. Quantifying the domestic electricity consumption for air-conditioning due to urban heat islands in hot arid regions. Appl Energy 2013;112:371–80.
[16] Li C, Zhou J, Cao Y, Zhong J, Liu Y, Kang C, et al. Interaction between urban microclimate and electric air-conditioning energy consumption during high temperature season. Appl Energy 2014;117:149–56.
[17] Kolokotroni M, Ren X, Davies M, Mavrogianni A. London's urban heat island: impact on current and future energy consumption in office buildings. Energy Build 2012;47:302–11.
[18] Kolokotroni M, Giridharan R. Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. Sol Energy 2008;82:986–98.
[19] Magli S, Lodi C, Lombroso L, Muscio A, Teggi S. Analysis of the urban heat island effects on building energy consumption. Int J Energy Environ Eng 2014;6:91–9.
[20] Street M, Reinhart C, Norford L, Ochsendorf J. Urban heat island in Boston – an evaluation of urban air-temperature models for predicting building energy use. In: Proceedings of BS2013: 13th conference of international building performance simulation association, Chambéry, France; August 26–28, 2013.
[21] Chen D, Ren Z, Wang C-H, Thatcher M, Wang X. Urban heat Island on Australian housing energy consumption healthy buildings, Brisbane, Queensland; 2012.
[22] Paolini R, Zani A, MeshkinKiya M, Castaldo VL, Pisello AL, Antretter F, et al. The hygrothermal performance of residential buildings at urban and rural sites: sensible and latent energy loads and indoor environmental conditions. Energy Build 2017;152:792–803.
[23] Founda D, Santamouris M. Synergies between Urban Heat Island and Heat Waves in Athens (Greece), during an extremely hot summer (2012). Sci Reports 7(1); December 2017: doi:10.1038/s41598-017-11407-6.
[24] Giannopoulou K, Livada I, Santamouris M, Saliari M, Assimakopoulous M, Caouris YG. On the characteristics of the summer urban heat island in Athens, Greece. Sustain Cities Soc 2011;1:16–28.
[25] Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings – a review. Energy Build 2015;98:119–24.
[26] Climate and more sustainable cities: climate information for improved planning and management of cities (Producers/Capabilities Perspective). Procedia Environ Sci 2010; p. 247–274.
[27] Hassid S, Santamouris M, Papanikolaou N, Linardi A, Klitsikas N, Georgakis C, et al. The effect of the Athens heat island on air conditioning load. Energy Build 2000;32:131–41.
[28] Kandya A, Mohan M. Mitigating the Urban Heat Island effect through building envelope modifications. Energy Build 2018;164:266–77.
[29] Akbari H, Konopacki S. Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy 2005;33(6):721–56.
[30] Ihara T, Kikegawa Y, Asahi K, Genchi Y, Kondo H. Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. Appl Energy 2008;85:12–25.
[31] Kikegawa Y, Genchi Y, Kondo H, Hanaki K. Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. Appl Energy 2006;83:649–68.
[32] Sailor DJ, Dietsch N. The urban heat island Mitigation Impact Screening Tool (MIST). Environ Modell Softw 2007;22(10):1529–41.
[33] Kikegawa Y, Genchi Y, Yoshikado H, Kondo H. Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. Appl Energy 2003;76:449–66.
[34] Tselepidaki I, Santamouris M, Asimakopoulos DN, Kontoyiannidis S. On the variability of cooling degree-days in an urban environment: application to Athens, Greece. Energy Build 1994;21(2):93–9.
[35] Kohler M, Blond N, Clappier A. A city scale degree-day method to assess building space heating energy demands in Strasbourg Eurometropolis (France). Appl Energy 2016;184:40–54.
[36] Nik VM. Making energy simulation easier for future climate – Synthesizing typical and extreme weather data sets out of regional climate models (RCMs). Appl Energy 2016;177:204–26.
[37] Bechtel B, Zakšek K, Oßenbrügge J, Kaveckis G, Böhner J. Towards a satellite based monitoring of urban air temperatures. Sustain Cities Soc 2017;34:22–31.
[38] Ma J, Cheng JCP. Estimation of the building energy use intensity in the urban scale by integrating GIS and big data technology. Appl Energy 2016;183:182–92.
[39] Li W, Zhou Y, Cetin K, Eom J, Wang Y, Chen G, et al. Modeling urban building energy use: a review of modelling approaches and procedures. Energy 2017;141:2445–57.
[40] Frayssinet L, Merlier L, Kuznik F, Hubert J-L, Milliez M, Roux J-J. Modeling the heating and cooling energy demand of urban buildings at city scale. Renew Sustain Energy Rev 2018;81:2318–27.
[41] Yang Z, Roth J, Jain RK. DUE-B: Data-driven urban energy benchmarking of buildings using recursive partitioning and stochastic frontier analysis. Energy Build 2018;163:58–69.
[42] Kontokosta CE, Tull C. A data-driven predictive model of city-scale energy use in buildings. Appl Energy 2017;197:303–17.
[43] Chen Y, Hong T, Piette MA. Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis. Appl Energy 2017;205:323–35.
[44] Robinson D, Haldi F, Kämpf JH, Leroux P, Perez D, Rasheed A, et al. "CITYSIM: comprehensive micro-simulation of resource flows for sustainable urban planning". In: Proceedings of international IBPSA conference; 2009. p. 1083–90.
[45] Quan SJ, Li Q, Augenbroe G, Brown J, Yang PP-J. Urban data and building energy modeling: a GIS-based urban building energy modeling system using the urban-EPC engine. In: Geertman S, Joseph Ferreira J, Goodspeed R, Stillwell J, editors. Plan. support syst. smart cities. Springer; 2015, p. 447–69. doi: 10.1007/978-3-319-18368-8.
[46] Zhang Q. Residential energy consumption in China and its comparison with Japan, Canada, and USA. Energy Build 2004;36:1217–25.
[47] Summerfield AJ, Lowe RJ, Oreszczyn T. Two models for benchmarking UK domestic delivered energy. Build Res Inform 2009;38(1):12–24.
[48] Zinzi M, Carnielo E. Impact of urban temperatures on energy performance and thermal comfort in residential buildings. The case of Rome, Italy. Energy Build 2017;157:20–9.
[49] Roma Capitale – Dipartimento Tutela ambientale e del Verde – ProtezioneCivile. Relazione sullo Stato dell'Ambiente – Natura e verde pubblico; 2012. p. 120.
[50] Chiesura A. Gestione ecosistemica delle aree verdi urbane: analisi e proposte, ISPRA – Istituto Superiore per la protezione e la ricerca ambientale; 2009, ISBN978-88-448-0386-5.
[51] ARPA Lazio. Technical sheet of measuring station AL004. www.arpalazio.net/main/aria/doc/RMT/Schede/AL004.pdf.
[52] TRNSYS 16. www.trnsys.com.
[53] UNI/TS 11300: Parte 1 - Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale (Evaluation of energy need for space heating and cooling); 2014.